

Deeply Virtual Pseudoscalar Meson Production at Jefferson Lab and Transversity GPDs

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The cross section of the exclusive π^0 and η electroproduction reaction $ep \rightarrow e'p'\pi^0/\eta$ was measured at Jefferson Lab with a 5.75-GeV electron beam and the CLAS detector. Differential cross sections $d^4\sigma/dtdQ^2dx_Bd\phi$ and structure functions $\sigma_T + \epsilon\sigma_L$, σ_{TT} and σ_{LT} as functions of t were obtained over a wide range of Q^2 and x_B . The data are compared with the GPD based theoretical models. Analyses find that a large dominance of transverse processes is necessary to explain the experimental results. Generalized form factors of the transversity GPDs $\langle H_T \rangle^{\pi,\eta}$ and $\langle \bar{E}_T \rangle^{\pi,\eta}$ were directly extracted from the experimental observables for the first time. It was found that GPD \bar{E}_T dominates in pseudoscalar meson production. The combined π^0 and η data opens the way for the flavor decomposition of the transversity GPDs. The first ever evaluation of this decomposition was demonstrated.

I. INTRODUCTION

Understanding nucleon structure in terms of the fundamental degrees of freedom of Quantum Chromodynamics (QCD) is one of the main goals in the theory of strong interactions. In recent years it became clear that exclusive reactions may provide information about hadron structure encoded in so-called Generalized Parton Distributions [1, 2] (GPDs). For each quark flavor q there are eight GPDs. Four correspond to parton helicity-conserving (chiral-even) processes, denoted by H^q , \tilde{H}^q , E^q and \tilde{E}^q , and four correspond to parton helicity-flip (chiral-odd) processes [3, 4], H_T^q , \tilde{H}_T^q , E_T^q and \tilde{E}_T^q . The GPDs depend on three kinematic variables: x , ξ and t . In a symmetric frame, x is the average longitudinal momentum fraction of the struck parton before and after the hard interaction and ξ (skewness) is half of the longitudinal momentum fraction transferred to the struck parton. The skewness can be expressed in terms of the Bjorken variable x_B as $\xi \simeq x_B/(2 - x_B)$. Here $x_B = Q^2/(2p \cdot q)$ and $t = (p - p')^2$, where p and p' are the initial and final four-momenta of the nucleon.

When the theoretical calculations for longitudinal virtual photons were compared with the JLab π^0 data [5, 6] they were found to underestimate the measured cross sections by more than an order of magnitude in their accessible kinematic regions. The failure to describe the experimental results with quark helicity-conserving operators stimulated a consideration of the role of the chiral-odd quark helicity-flip processes. Pseudoscalar meson electroproduction, and in particular π^0 production in the reaction $ep \rightarrow e'p'\pi^0$, was identified [7–9] as especially sensitive to the quark helicity-flip subprocesses. During the past few years, two parallel theoretical approaches - [7, 10] (GL) and [8, 9] (GK) have been developed utilizing the chiral-odd GPDs in the calculation of pseudoscalar meson electroproduction. The GL and GK approaches, though employing different models of GPDs, lead to *transverse* photon amplitudes that are much larger than the longitudinal amplitudes.

II. DEFINITION OF STRUCTURE FUNCTIONS

The unpolarized reduced meson cross section is described by 4 structure functions σ_T , σ_L , σ_{TT} and σ_{LT}

$$2\pi \frac{d^2\sigma(\gamma^*p \rightarrow p\pi^0)}{dtd\phi_\pi} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{dt} \cos \phi.$$

References [9, 10] obtain the following relations for unpolarized structure functions:

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'} \frac{1}{Q^4} \left\{ (1 - \xi^2) \left| \langle \tilde{H} \rangle \right|^2 - 2\xi^2 \text{Re} \left[\langle \tilde{H} \rangle^* \langle \tilde{E} \rangle \right] - \frac{t'}{4m^2} \xi^2 \left| \langle \tilde{E} \rangle \right|^2 \right\}, \quad (1)$$

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'Q^4} \left[(1 - \xi^2) \left| \langle H_T \rangle \right|^2 - \frac{t'}{8m^2} \left| \langle \bar{E}_T \rangle \right|^2 \right], \quad (2)$$

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'Q^4} \xi \sqrt{1-\xi^2} \frac{\sqrt{-t'}}{2m} \text{Re} \left[\langle H_T \rangle^* \langle \tilde{E} \rangle \right], \quad (3)$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'Q^4} \frac{t'}{16m^2} |\langle \tilde{E}_T \rangle|^2, \quad (4)$$

Here m is the mass of the proton, $t' = t - t_{min}$, where $|t_{min}|$ is the minimum value of $|t|$ corresponding to $\theta_\pi = 0$, $k'(Q^2, x_B)$ is a phase space factor and $\tilde{E}_T = 2\tilde{H}_T + E_T$. The brackets $\langle H_T \rangle$ and $\langle \tilde{E}_T \rangle$ denote the convolution of the elementary process $\gamma^* q \rightarrow q\pi^0$ with the GPDs H_T and \tilde{E}_T . We call them generalized form factors.

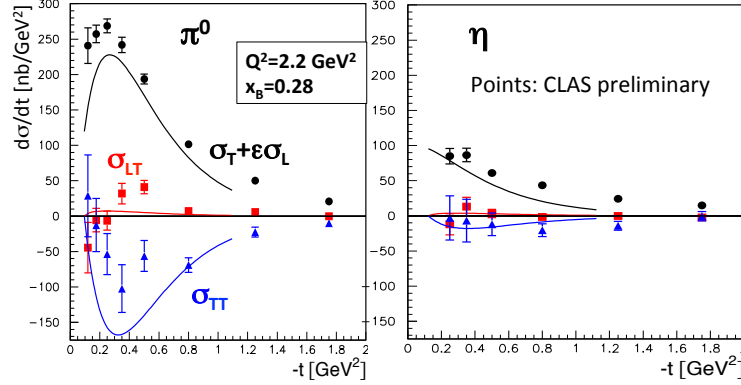


FIG. 1: (Color online) Structure functions $\sigma_T + \epsilon\sigma_L$ (black), σ_{TT} (blue) and σ_{LT} (red) as a function of $-t$ for π^0 (left) and η (right) exclusive electroproduction for kinematic point ($Q^2 = 2.2 \text{ GeV}^2, x_B = 0.28$). Data points: CLAS, preliminary. Curves: theoretical predictions produced with the GK handbag model.

III. EXPERIMENTAL DATA

Cross section of the reaction $ep \rightarrow ep\pi^0$ measured by the CLAS collaboration at Jlab at 1800 kinematic points in bins of Q^2 , x_B , t and ϕ were published in Refs. [5] and [6]. Structure functions $\sigma_U = \sigma_T + \epsilon\sigma_L$, σ_{LT} and σ_{TT} have been obtained. These functions were compared with the predictions of the GPD models [9, 10]. CLAS confirmed that the measured unseparated cross sections are much larger than expected from leading-twist handbag calculations which are dominated by longitudinal photons. The same conclusion can be made in an almost model-independent way by noting that the structure functions σ_U and $|\sigma_{TT}|$ are comparable to each other while $|\sigma_{LT}|$ is quite small (see Fig.1). Cross section and structure functions for $ep \rightarrow e\eta p$ were also obtained in parallel. The comparison of the π^0 and preliminary η structure functions is shown in Fig. 1. σ_U drops by a factor of 2.5 for η in comparison with π^0 and σ_{TT} drops by a factor of 10. The GK GPD model [9] (curves) follows the experimental data. The inclusion of η data into consideration strengthens the statement about the transversity GPD dominance in the pseudoscalar electroproduction process.

IV. GENERALIZED FORM FACTORS

The squared magnitudes of the generalized form factors $|\langle H_T \rangle|^2$ and $|\langle \tilde{E}_T \rangle|^2$ may be directly extracted from the experimental data (see Eqs. 2 and 4) in the framework of GPD models.

$$\begin{aligned} |\langle \tilde{E}_T \rangle^{\pi,\eta}|^2 &= \frac{k'Q^4}{4\pi\alpha} \frac{16m^2}{t'} \frac{d\sigma_{TT}^{\pi,\eta}}{dt} \\ |\langle H_T \rangle^{\pi,\eta}|^2 &= \frac{2k'Q^4}{4\pi\alpha} \frac{1}{1-\xi^2} \left[\frac{d\sigma_T^{\pi,\eta}}{dt} + \frac{d\sigma_{TT}^{\pi,\eta}}{dt} \right]. \end{aligned} \quad (5)$$

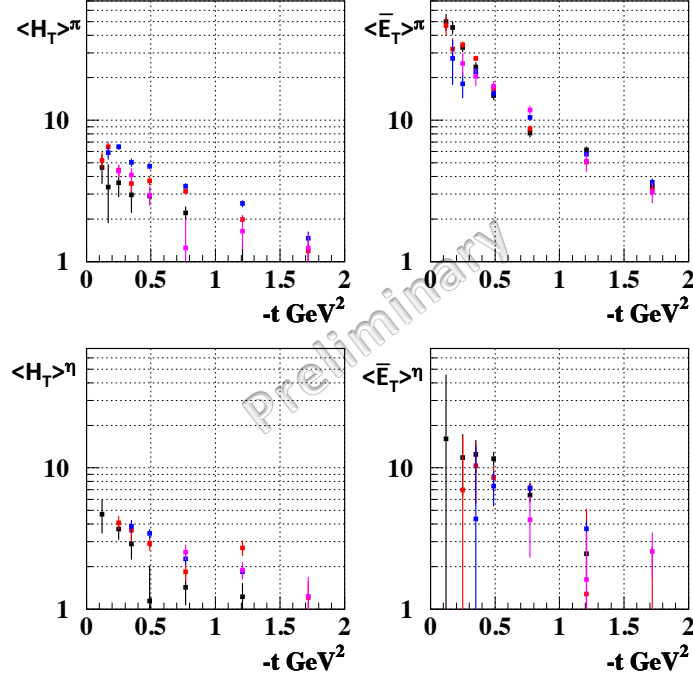


FIG. 2: (Color online) Data points: CLAS, preliminary. Top left: $|\langle H_T \rangle^\pi|$, top right: $|\langle \bar{E}_T \rangle^\pi|$, bottom left: $|\langle H_T \rangle^\eta|$, bottom right: $|\langle \bar{E}_T \rangle^\eta|$ as a function of $-t$ for different values of $(Q^2 \text{ [GeV}^2], x_B) = (1.2, 0.15)$ black, $(1.8, 0.22)$ red, $(2.2, 0.27)$ blue, $(2.7, 0.34)$ magenta.

Fig. 2 presents the modules of the generalized form factors $|\langle H_T \rangle^\pi|$, $|\langle \bar{E}_T \rangle^\pi|$, $|\langle H_T \rangle^\eta|$ and $|\langle \bar{E}_T \rangle^\eta|$ for 4 different kinematics. Note the dominance of the $|\langle \bar{E}_T \rangle|$ over $|\langle H_T \rangle|$ for both π^0 and η for all kinematics.

Generalized formfactors $|\langle H_T \rangle^\pi|$ and $|\langle \bar{E}_T \rangle^\pi|$ may be fitted by simple exponential function with good χ^2 . The result is shown in Fig. 3 for one of the kinematical point. Note that $|\langle \bar{E}_T \rangle^\pi|$ form factor has steeper t -slope than $|\langle H_T \rangle^\pi|$. This is the first attempt to evaluate generalized formfactors from the experimental data.

Fig. 4 presents the comparison of the generalized form factors $|\langle H_T \rangle|$ and $|\langle \bar{E}_T \rangle|$ for π^0 (blue) and η (red) for oner kinematical point ($Q^2=2.2$, $x_B=0.27$). These data will be used for the flavor decomposition in the next section.

V. FLAVOR DECOMPOSITION

In electroproduction the GPDs F_i appears in the following combinations

$$\begin{aligned} F_i^\pi &= \frac{1}{\sqrt{2}}[e_u F_i^u - e_d F_i^d] \\ F_i^\eta &= \frac{1}{\sqrt{6}}[e_u F_i^u + e_d F_i^d - 2e_s F_i^s] \end{aligned} \quad (6)$$

The q and \bar{q} GPDs contribute in the quark combinations $F_i^q - F_i^{\bar{q}}$. Hence there is no contribution from the strange quarks if we assume that $F_i^s \simeq F_i^{\bar{s}}$. For flavor decomposition we have to take into account the decay constants f_π and f_η , the chiral condensate constants $\mu_{\pi^0} = 2.57 \text{ GeV}$, $\mu_1 = 0.958 \text{ GeV}$ and $\mu_8 = 2.32 \text{ GeV}$, and the contribution from singlet and octet η states.[9]

$$F_i^\eta = F_i^\pi \left(\cos \theta_8 - \sqrt{2} \frac{\mu_1}{\mu_8} \frac{f_1}{f_8} \sin \theta_1 \right) \frac{f_8}{f_{\pi^0}} \frac{\mu_8}{\mu_{\pi^0}} = \frac{F_i^8}{k_\eta}, \quad (7)$$

where the mixing angles are: $\theta_8 = -21.2^\circ$ and $\theta_1 = -9.2^\circ$. The octet and singlet wave functions are very similar and the decay constants are close as well $f_8 = 1.26 f_\pi$ and $f_1 = 1.17 f_\pi$. The overall factor for the η meson is $k_\eta = 0.863$.

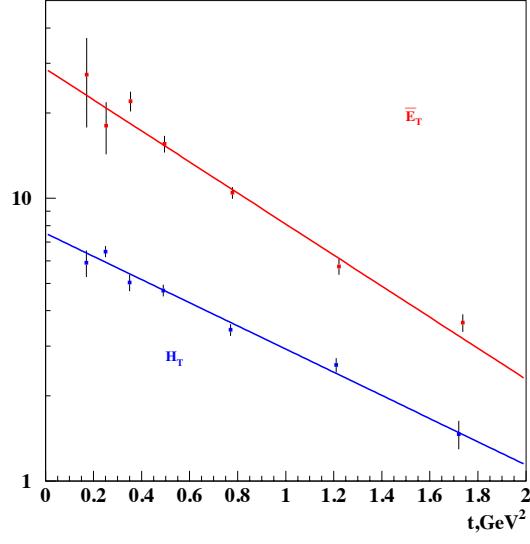


FIG. 3: (Color online) Preliminary. $|\langle H_T \rangle^\pi|$ (blue) and $|\langle \bar{E}_T \rangle^\pi|$ (red), as a function of $-t$, ($Q^2 = 2.2 \text{ GeV}^2$, $x_B=0.27$).

Using $e_u = \frac{2}{3}$ and $e_d = -\frac{1}{3}$ we will end up with equations

$$\begin{aligned} F_i^\pi &= \frac{1}{3\sqrt{2}}[2F_i^u + F_i^d] \\ k_\eta F_i^\eta &= \frac{1}{3\sqrt{6}}[2F_i^u - F_i^d]. \end{aligned} \quad (8)$$

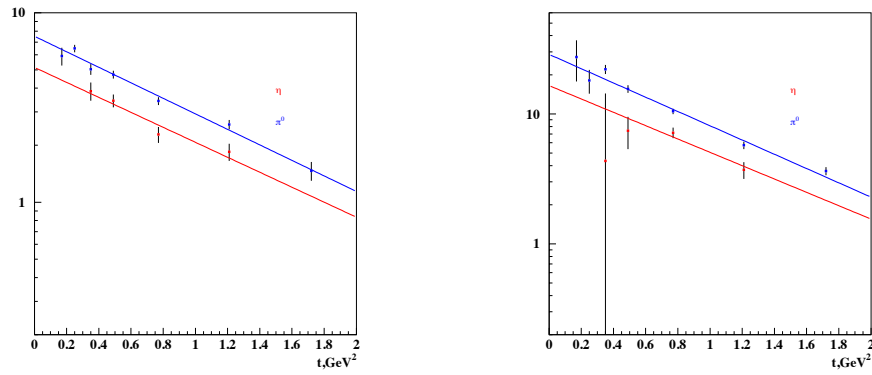


FIG. 4: (Color online) Preliminary. Left: $|\langle H_T \rangle^\pi|$ (blue) and $|\langle H_T \rangle^\eta|$ (red). Right: $|\langle \bar{E}_T \rangle^\pi|$ (blue) and $|\langle \bar{E}_T \rangle^\eta|$ (red); ($Q^2=2.2$, $x_B=0.27$).

Experimentally we have access only to the $|\langle F_i^\pi \rangle|^2$ and $|\langle F_i^\eta \rangle|^2$ (see Eq. 5). The final equation for the $\langle H_T \rangle$ convolution reads

$$\begin{cases} \frac{1}{18} |2\langle H_T \rangle^u + \langle H_T \rangle^d|^2 = |\langle H_T \rangle^\pi|^2 \\ \frac{1}{54} |2\langle H_T \rangle^u - \langle H_T \rangle^d|^2 = k_\eta^2 |\langle H_T \rangle^\eta|^2 \end{cases} \quad (9)$$

and similar equations for $\langle \bar{E}_T \rangle$. The solution of these equations will lead to the flavor decomposition of the transversity

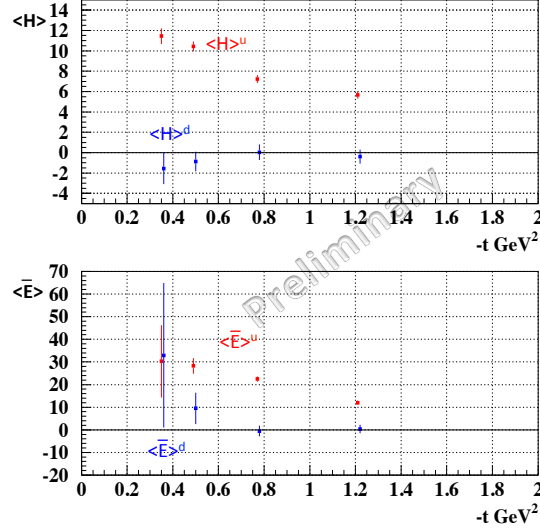


FIG. 5: (Color online) Preliminary. Top: Extracted $\langle H_T \rangle^u$ (red) and $\langle H_T \rangle^d$ (blue); Bottom: $\langle \bar{E}_T \rangle^u$ (red) and $\langle \bar{E}_T \rangle^d$ (blue), as a function of $-t$ for $Q^2 = 2.2 \text{ GeV}^2$ and $x_B = 0.27$.

GPDs $\langle H_T \rangle^u$ and $\langle H_T \rangle^d$ as well as $\langle \bar{E}_T \rangle^u$ and $\langle \bar{E}_T \rangle^d$. However the convolution integrals have real and imaginary parts. So it is impossible to solve these equations unambiguously with only two equations in hands. As a guidance we can estimate the form factors if we suppose that the relative phase $\Delta\phi$ between $\langle H_T \rangle^u$ and $\langle H_T \rangle^d$ equals 0 or 180 degrees. Ignoring an overall phase, the form factors are then real and we arbitrarily choose the solution with $\langle H_T \rangle^u$ and $\langle \bar{E}_T \rangle^u$ positive. Fig. 5 presents $\langle H_T \rangle^u$, $\langle H_T \rangle^d$, $\langle \bar{E}_T \rangle^u$ and $\langle \bar{E}_T \rangle^d$ for one kinematic point ($Q^2 = 2.2 \text{ GeV}^2$, $x_B = 0.27$) calculated in this assumption. Note the different signs of $\langle H_T \rangle^u$ and $\langle H_T \rangle^d$ convolutions and the same sign of $\langle \bar{E}_T \rangle^u$ and $\langle \bar{E}_T \rangle^d$.

VI. CONCLUSION

Differential cross sections of exclusive π^0 and η electroproduction have been obtained in the few-GeV region at more than 1800 kinematic points in bins of Q^2 , x_B , t and ϕ_π . Virtual photon structure functions σ_U , σ_{TT} and $d\sigma_{LT}$ have been obtained. It is found that σ_U and σ_{TT} are comparable in magnitude with each other, while σ_{LT} is very much smaller than either. Generalized form factors of the transversity GPDs $\langle H_T \rangle^{\pi,\eta}$ and $\langle \bar{E}_T \rangle^{\pi,\eta}$ were directly extracted from the experimental observables for the first time. It was found that the GPD \bar{E}_T dominates in pseudoscalar meson production. The combined π^0 and η data opens the way for the flavor decomposition of the transversity GPDs. Within some simplifying assumptions, the decomposition has been demonstrated for the first time.

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- [1] X. Ji, *Phys. Rev. Lett.* **78**, 610 (1997); *Phys. Rev. D* **55**, 7114 (1997).
 - [2] A.V. Radyushkin, *Phys. Lett. B* **380**, 417 (1996); *Phys. Rev. D* **56**, 5524 (1997).
 - [3] P. Hoodbhoy and X. Ji, *Phys. Rev. D* **58**, 054006 (1998).
 - [4] M. Diehl, *Phys. Rep.* **388**, 41 (2003) and references within.
 - [5] I. Bedlinskiy *et al.* (CLAS Collaboration), *Phys. Rev. Lett.* **109**, 112001 (2012).
 - [6] I. Bedlinskiy *et al.* (CLAS Collaboration), *Phys. Rev. C* **90**, 025205 (2014).
 - [7] S. Ahmad, G. R. Goldstein and S. Liuti, *Phys. Rev. D* **79**, 054014 (2009).
 - [8] S. V. Goloskokov and P. Kroll, *Eur. Phys. J. C* **65**, 137 (2010).
 - [9] S. V. Goloskokov and P. Kroll, *Eur. Phys. J. A* **47**, 112 (2011).
 - [10] G. Goldstein, J. O. Gonzalez-Hernandez and S. Liuti, *Phys. Rev. D* **84**, 034007 (2011); *Int. J. Mod. Phys. Conf. Ser.* **20**, 222 (2012); *J. Phys. G: Nucl. Part. Phys.* **39** 115001 (2012).